

Acoustical Scattering, Propagation, and Attenuation Caused by Two Abundant Pacific Schooling Species: Humboldt Squid and Hake

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LONG-TERM GOALS

Our long-term goal is to predict the acoustic characteristics expected from aggregations of hake and jumbo squid off the west coast of North America within the frequency range of tactical, low to mid-frequency naval sonars.

OBJECTIVES

Our objectives are to:

- Measure the material properties of jumbo squid and hake
- Characterize the inhomogeneity of these properties and identify important scattering mechanisms
- Develop target strength models for both species as a function of frequency and depth
- Measure target strength of individuals of both species to validate models
- Measure in situ the spatial and temporal distributions of squid and hake
- Develop propagation, attenuation, and scattering models for these aggregations

APPROACH

To accomplish our goal of predicting the in situ scattering, propagation, and attenuation from monospecific and mixed schools of squid and hake, we will combine information from field surveys of aggregations with measurements of the biological and physical habitat surrounding these aggregations to identify key parameters related to the distribution and behavior of these animals. These parameters will be used to create probability surfaces for aggregations of various types. These surfaces will be combined with the acoustic scattering models to predict the range of acoustic scattering expected from this biologically created acoustic uncertainty under given environmental conditions.

WORK COMPLETED

As part of an ONR supported cruise (26 July – 10 August, 2012), we collected physical samples and in situ data to be used in understanding and predicting the scattering, propagation, and attenuation from monospecific and mixed schools of squid and hake. Schooling fish can cause strong acoustic scattering and attenuation, dramatically altering the propagation of sound, particularly in coastal environments. Off the west coast of the United States, an area important for acoustical testing and tactical exercises, the most abundant species by biomass is Pacific hake, *Merluccius productus*, a fish with an air-filled swimbladder that averages 50 cm in length with maximum lengths of up to 90 cm. A more recent immigrant to these waters, is the similarly sized and highly abundant jumbo or Humboldt squid, *Dosidicus gigas*, which lacks any air-filled cavities. Before the invasion of Humboldt squid into the California current in the mid 1990's, aggregations of hake were shown to be the strongest biological sources of low frequency (e.g. hundreds of Hz to tens of kHz) acoustic scattering off the US West coast. Given the similarities observed in the scattering of individual hake and jumbo squid, it is highly likely that aggregations of squid show similarly strong scattering within the frequency band of tactical naval sonars.

During this field effort, we collected in situ data from aggregations of Pacific hake that ranged in length from 20 to 50 cm. These aggregations ranged from discrete schools to extensive layers sometimes nested within each other. These hake aggregations frequently overlapped with aggregations of other organisms including larval fish with large swimbladders, myctophids that make up the deep scattering layer, and Humboldt squid. We were able to measure aggregations under this full range of conditions at frequencies ranging from 10 kHz up to 200 kHz, including broadband measurements at tens of kHz.

As part of our in situ observations, we were able to make in situ measurements of target strength over the full frequency range used for a large number of individuals. In addition to in situ data, a large number of samples of the species observed within our study area was obtained. In addition to being used for ground-truthing, the material properties (density contrast and sound speed) of more than 1500 individuals were measured. This large sample size combined with careful measures of swimbladder shape, reproductive condition, stomach fullness, and other independent variables will allow us to examine the effects of biological variability on acoustic characteristics of these animals. Finally, a number of these individual animals were preserved for characterization using CT scanning for detailed acoustical modeling.

A significant result of our field experiment was unexpected measurements in groups of scatterers, including squid and hake, but also smaller scatterers like myctophids. We found that measurements of scattering of individuals within these groups changed with range in ways that cannot be explained by

biological variation or our understanding of physical processes. We suspected problems in existing analysis approaches and designed an *in situ* multiple scattering experiment to identify the problem and examine multiple scattering more generally. Completed this summer, the experiment involved observing varying numerical densities and spatial distributions of known targets. Some experiments involved using multiples of only one sized target while others involved multiple sized targets to replicated mixed scattering aggregations.

We have completed the measurement and analysis of the material properties (density and sound speed contrast) of the two target species (Pacific Hake, Humboldt Squid) (Objective #1, Figure 1) as well as several other taxa that were found in the area and may be acoustically important (e.g. myctophids; euphausiids, other crustaceans, larval fish and squid, and gelatinous zooplankton; Becker and Warren, 2014; Becker and Warren, *in review*).



Figure 1. Specimens collected during the research cruise whose material properties were analyzed including (from left to right): euphausiids, myctophids, Pacific hake, Humboldt squid.

A key goal for this project is to develop acoustic scattering models for real aggregations. We have constructed an experimental apparatus for conducting multiple-scatterer aggregation experiments using inert targets. We have obtained University IACUC approval and NY DEC approval to collect local fish which will be used with this system to examine whether the results from the inert targets can be applied to actual biological targets. These data will be used to test the validity and accuracy of the theoretical scattering, attenuation, and propagation models developed in this project.

RESULTS

Material properties

For Humboldt squid, all “soft” body parts (mantle, arm, tentacle, braincase, and eye) had density contrast values (g) that were 1-6% higher than the surrounding seawater (Figure 2). These values are comparable to those for other fluid-like scatterers, although there was wide variability in the density contrast for some parts, specifically the squid braincase, a part implicated in previous work as a possible source of scattering

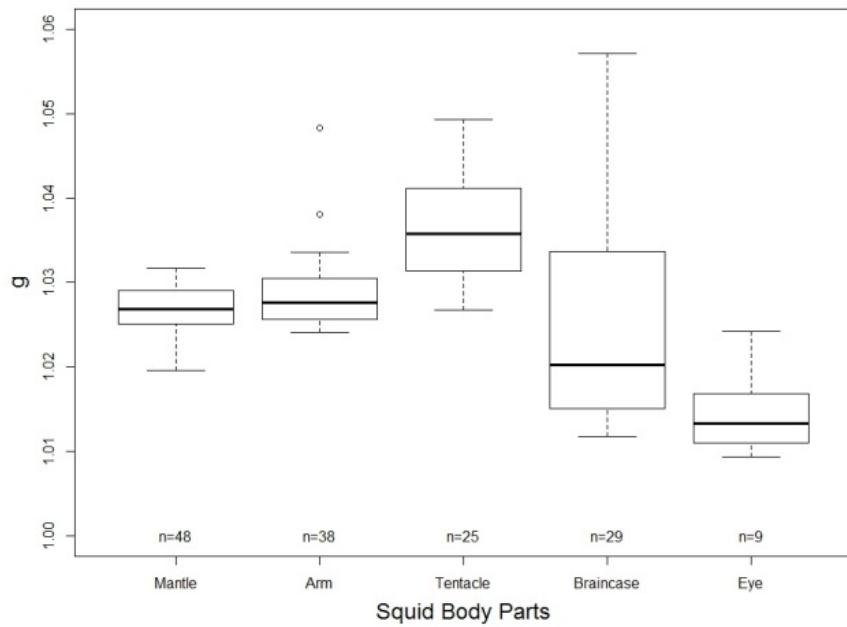


Figure 2: Density contrast (g) for “soft” Humboldt squid body parts measured. The lower line of each box represents the 1st quartile, the middle bolded line represents the median, and the top line of the box represents the 3rd quartile. The whiskers of the plot represent the minimum and maximum values excluding the outliers, and the circles mark any outliers.

The “hard” parts (beak, pen) of the Humboldt squid had larger g values than the “soft” parts as would be expected (Figure 3). These measurements were made in the laboratory post-cruise as the method used at sea could not measure g values that were this large. Squid beaks were significantly more dense than any other part of the squid.

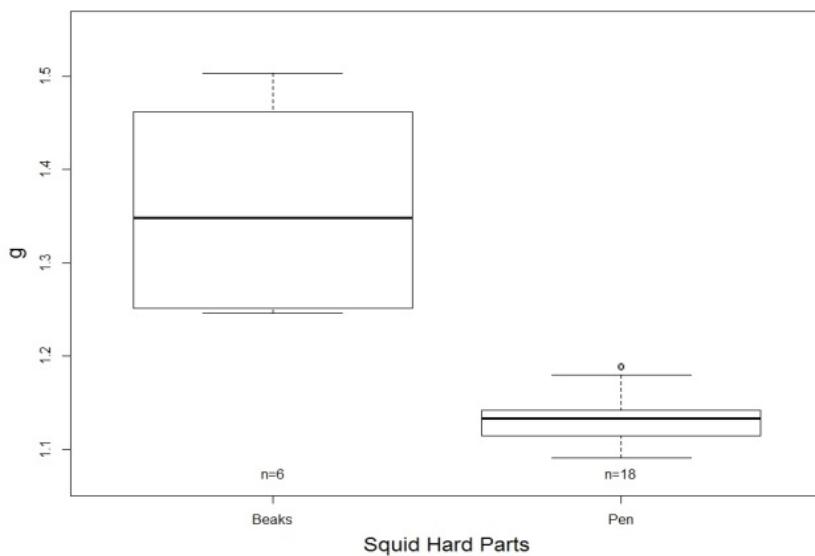


Figure 3: Density contrast (g) for Humboldt squid hard parts. The lower line of each box represents the 1st quartile, the middle bolded line represents the median, and the top line of the box represents the 3rd quartile. The whiskers of the plot represent the minimum and maximum values excluding the outliers, and the circles mark any outliers.

In general, Pacific hake tissue had density contrast values similar to the values for squid “soft” parts; but the hake tissue values were larger and varied less than tissue from other fish (myctophids) (Figure 4). Myctophid fish tissue values varied greatly particularly between the lantern fish and headlight fish species. Unfortunately, we did not collect enough individual squid and hake to examine variability between individuals from different geographic regions or other characteristics (size, age). We did examine some of these relationships for the animals that we did catch enough individuals of which were primarily different zooplankton species. Zooplankton density contrast values varied both within and among different species (Figure 5) as well as for euphausiids from different geographic areas (Figure 6). We are examining whether these differences are the result of differences in animal size or environmental conditions.

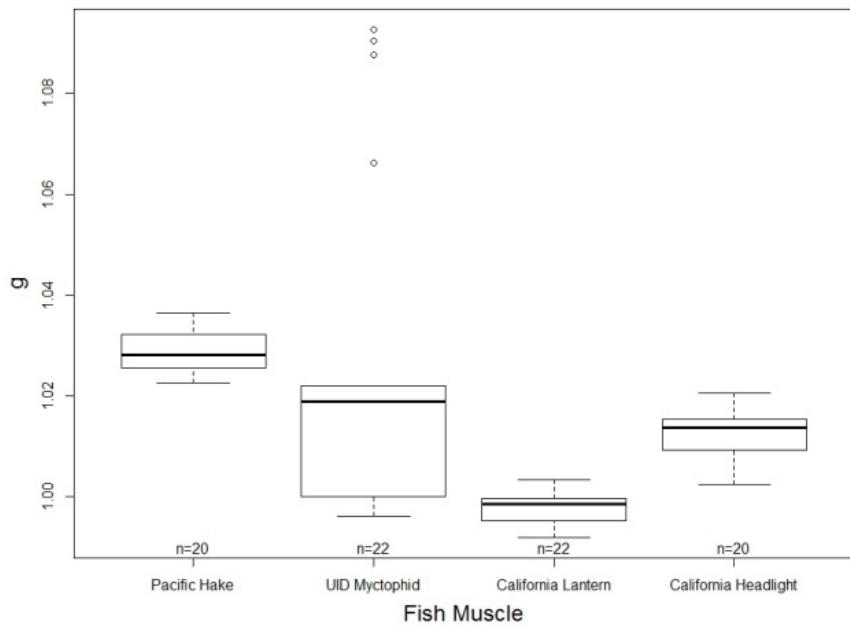


Figure 4: Density contrast (g) for Pacific hake and myctophid muscle measured. The lower line of each box represents the 1st quartile, the middle bolded line represents the median, and the top line of the box represents the 3rd quartile. The whiskers of the plot represent the minimum and maximum values excluding the outliers, and the circles mark any outliers.

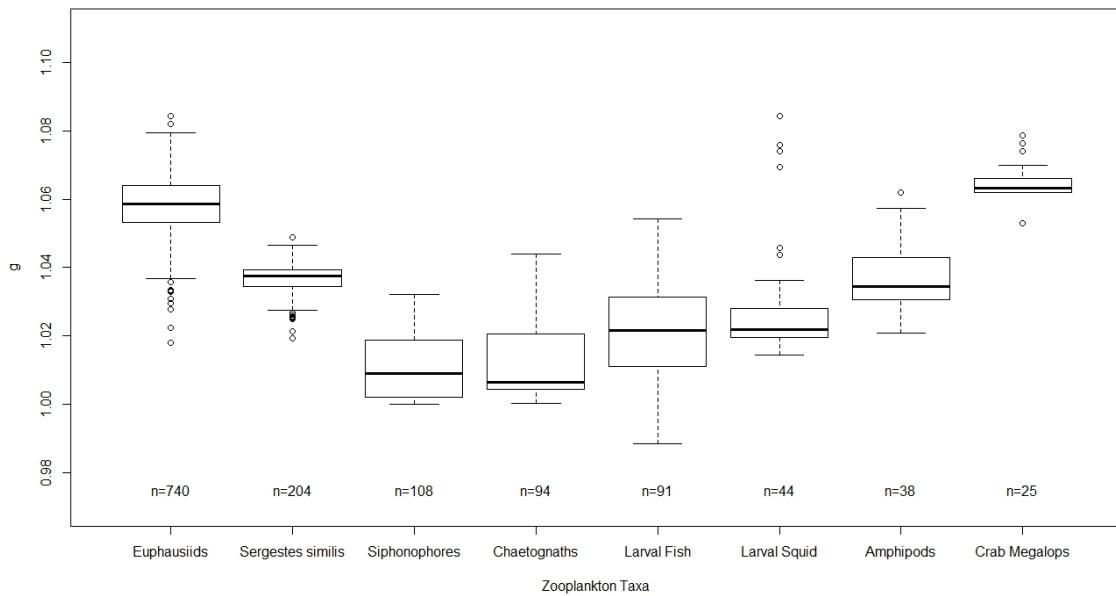


Figure 5: Density contrast (g) for seven different zooplankton taxa. The lower line of each box represents the 1st quartile, the middle bolded line represents the median, and the top line of the box represents the 3rd quartile. The whiskers of the plot represent the minimum and maximum values excluding the outliers, and the circles mark any outliers.

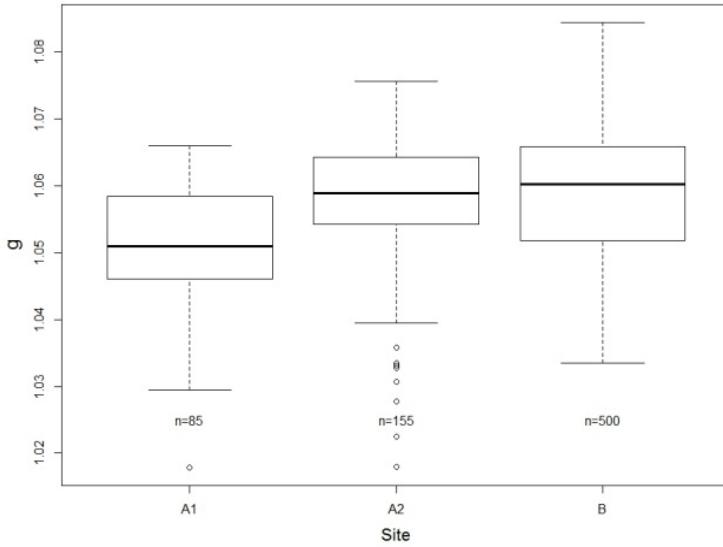


Figure 6: Euphausiid density contrast at the three different sample sites, A1, B, and A2. The lower line of each box represents the 1st quartile, the middle bolded line represents the median, and the top line of the box represents the 3rd quartile. The whiskers of the plot represent the minimum and maximum values excluding the outliers, and the circles mark any outliers.

Sound speed contrast measurements were made for several different taxa including Humboldt squid and Pacific hake (Table 1). The measurement technique used requires a minimum volume of organisms (or parts of organisms) so measurements were made on multiple animals or pieces of animal tissue. Interesting findings include: hake muscle tissue h was very close to 1 while g was 2-4% more dense than surrounding seawater and that the squid braincase was composed of different portions with different firmnesses (referred to as “squishy” and “firm” in the lab book notes). The softer braincase had an h value less than unity while the firm braincase part had an h value greater than 1. Since acoustic scattering occurs whenever there are density or soundspeed contrasts, this may suggest that the braincase is an important scattering mechanism within the Humboldt squid.

Table 1: The mean and standard deviation (sd) of speed contrast (h) measurements for all zooplankton taxa, fish muscle, and squid body parts measured. The number of replicates is n.

Sound Speed Contrast (h)			
Species/Body Part	n	mean	sd
Euphausiids	17	1.019	0.0092
Shrimp (<i>Sergestes similis</i>)	2	1.028	<0.0001
Pacific Hake Muscle	7	0.9945	0.0148
UID Myctophids	1	1.015	n/a
Humboldt Squid Mantle	3	1.023	0.0045
Humboldt Squid Braincase - squishy	1	0.9422	na
Humboldt Squid Braincase - firm	1	1.0250	na

Material property inhomogeneities and identification of scattering mechanisms

Whole individual specimens of Pacific hake and Humboldt squid as well as myctophids were frozen during the cruise for later analysis to examine the three-dimensional structure of the material properties of these organisms. Since these specimens are extremely valuable and irreplaceable, we have begun the process of determining which method will provide the highest-quality data regarding the 3-D structure of the material properties and scattering mechanisms in these animals. Stony Brook University's Imaging Center has a "mouse CT" scanner which provides very high resolution (~70 micron) slices of the density contrast of a specimen. However, at this fine resolution, specimen size is limited. Using local fish specimens, we have collected preliminary data to determine whether using the high-resolution of this device is needed. Six local fish species containing swimbladders (juvenile blackfish, juvenile scup, mummichog, juvenile seabass, juvenile weakfish, juvenile winter flounder and Atlantic silverside) and two local squid (long-fin *Loligo* sp.) have been scanned (Figure 7). The scans clearly show the bones and swimbladder in the animals as well as differences within the tissues/organs of the fish. Additionally, data collected show that the feeding state of the animal (including its type of prey) may affect the scattering characteristics of the animal especially if the animal has eaten hard-shelled mollusc prey.

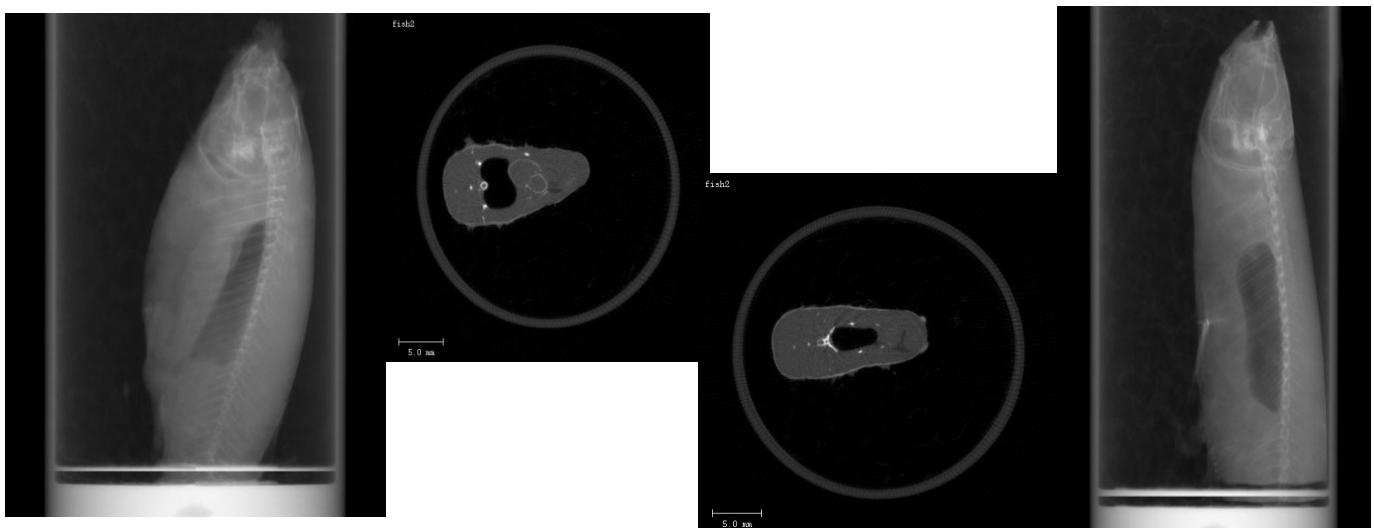


Figure 7. A dorsal scan (similar to an x-ray) of a mummichog (left), two 2-D slices through the mummichog showing the swimbladder (empty/black space inside fish), spine (just to left of swimbladder), and different tissues (right of swimbladder) (middle two images), and a dorsal scan of an Atlantic silverside (right).

The measurements and samples obtained are providing data on the material properties of animals, the variables that drive inhomogeneity of these properties, and helping us to identify important scattering mechanisms in soft-bodied animals. All of these data will be used to develop species and depth specific target strength models that will be validated against the data collected in situ. These individual models will be combined with field observations of the spatial and temporal distributions of squid and hake to create predictions of the acoustic characteristics expected from aggregations of hake and jumbo squid off the west coast of North America within the frequency range of tactical, low to mid-frequency naval sonars.

Multiple Scatterer Field Experiment

Acoustic backscatter data from aggregations of hake and squid measured during the 2012 fieldwork (and in other projects) contained interesting patterns with respect to the Target Strength of detected individual targets and their distance from the echosounder. In order to examine whether these findings were the result of scattering from multiple targets within aggregations or a data processing / target-detection artifact, we designed a series of field experiments using standard targets with identical TS values. These experiments took place in August 2014 off the coast of Lanai, Hawaii (and ended when two hurricanes passed through the area).

Experiments used EK60 echosounders operating at 38, 70, 120, and 200 kHz and standard targets (steel spheres) ranging in diameter from 3 mm to 25 mm (Figure 8, Table II). We examined the effects of pulse length, target size, target numerical density (# targets / m³), and aggregation composition (one type of target, multiple types of targets within an aggregation) on the measured acoustic backscatter.

Single targets were tracked as they sank vertically over approximately 100 m of the water column. Multiple targets (ranging from 2-5 to up to 500+) were dropped adjacent to the echosounder array to examine target identification and discrimination and multiple scattering effects. Preliminary analysis of the data from these experiments suggests that standard target detection algorithms may produce range-biased measures of TS. We will use these experimental findings in conjunction with our multiple scattering models (as well as field-collected data from aggregations of fish) to examine how biological aggregations of animals scatter sound.

Table II. Theoretical Target Strength values for the standard targets used in the experiment.

Target size (mm)	TS at 38 kHz (dB)	TS at 70 kHz (dB)	TS at 120 kHz (dB)	TS at 200 kHz (dB)
3.175	-82.9	-73.0	-65.8	-64.2
6.35	-65.7	-58.4	-60.6	-55.5
7.9375	-60.7	-55.7	-55.9	-53.8
9.525	-56.8	-55.2	-51.3	-52.1
12.7	-51.9	-53.7	-50.6	-51.3
25.4	-45.5	-42.5	-42.5	-43.1



Figure 8. Multiple frequency echosounder array on boat deck (left) and in water (middle). Standard targets were steel spheres ranging in size from 3 to 25 mm (right).

WORK COMPLETED

We are continuing to analyze the TS data from our inert target experiments, but have begun a parallel effort of analysis of biological targets (fish) that occupy a narrow range of depth strata (thereby removing any range effects on single-target detection algorithms that we have encountered with the inert target data). Backscattering data have been collected on hundreds of fish schools composed of monospecific (size, species) aggregations of Atlantic menhaden (*Brevoortia tyrannus*) which form very large and dense schools which can be problematic for acoustic backscatter data analysis (Figure 9). A key characteristic of these aggregations are the “rain cloud” that appears underneath schools. This is the result of multiple scattering processes (i.e. sound waves are reflecting from multiple fish (thereby lengthening the return time of their echoes which makes these multiple scattering echoes both weaker (change in color from red/brown to blue) and appear to be deeper in the water column (due to the increased path length). By analyzing schools which have this characteristic, we are confident that multiple scattering processes are occurring within the school.

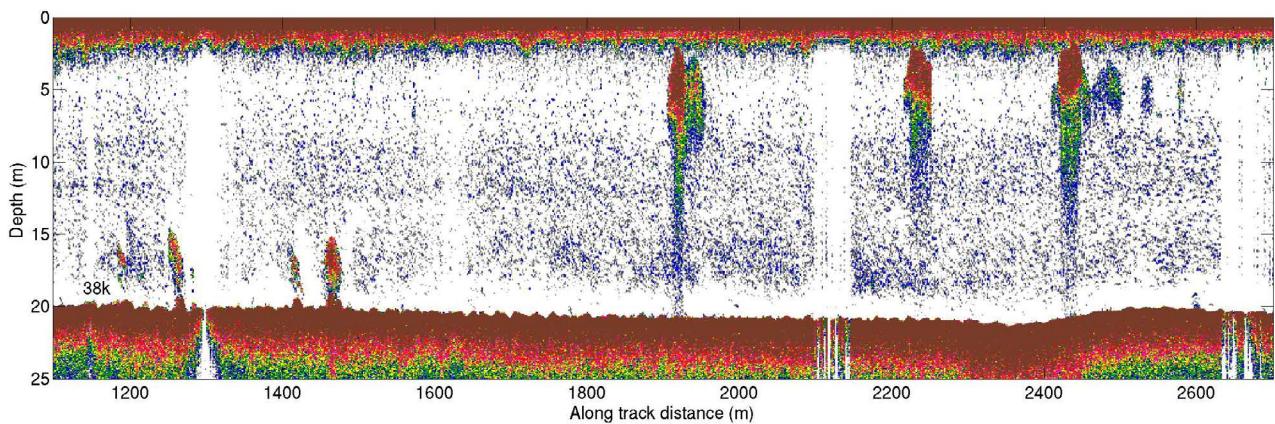


Figure 9. Dense schools of fish where multiple scattering processes occur have “rain clouds” of weaker scattering that occur beneath the actual school. Three schools of Atlantic menhaden exhibit this phenomena in this 38 kHz echogram.

In order to generate abundance and biomass estimates for organisms using active acoustics, one assumption that can be made is that each echo return is one organism. However, in dense aggregations, echoes can reflect off of multiple organisms which will 1) alter the characteristics of the individual echoes; 2) alter the scattering characteristics of the aggregation (including the spatial extent of the school); and 3) complicate the ability of discrimination and identification algorithms designed for schools where multiple scattering processes are not occurring. Consequently, the development of single target detection algorithms and other diagnostic techniques to discern individual acoustic targets from multiple scatterer and multiple-scattering processes is key for better understanding of the scattering processes. For this report, we present an illustrative case study (Figure 10) of the analyses currently being undertaken to better understand this phenomena.

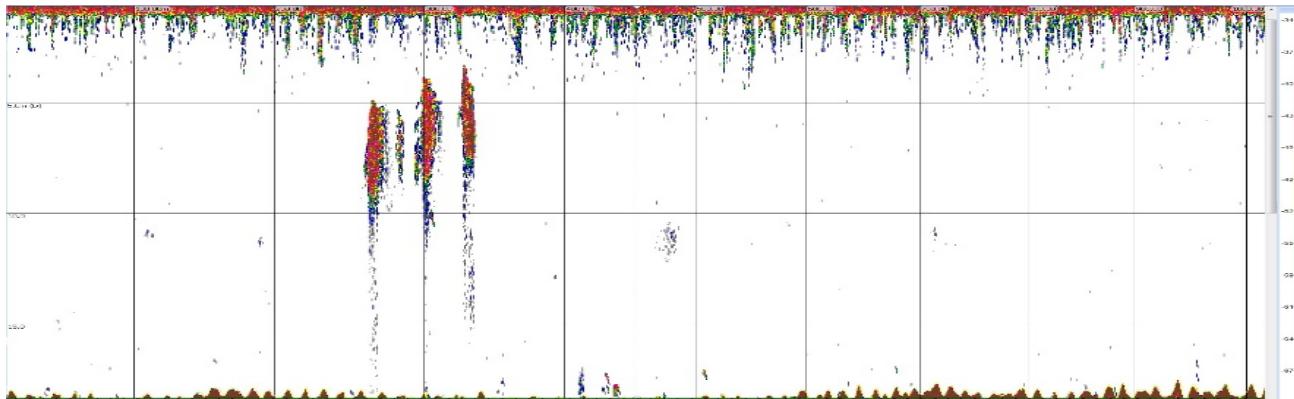


Figure 10. Raw volumetric acoustic backscatter echogram showing multiple menhaden schools. The blue “rain cloud” underneath each acoustic aggregation is a general indicator that multiple scattering is occurring.

With a split-beam echosounder, specific information regarding the position of acoustic targets can be determined which allows for better approximations of each target's relative target strength. Target strength (TS) is primarily a function of morphological (e.g., body length, swim bladder size) and physiological (e.g., lipid content) parameters. Within a typical aggregation, the distribution of target strength values appears to have several peaks (Figure 11).

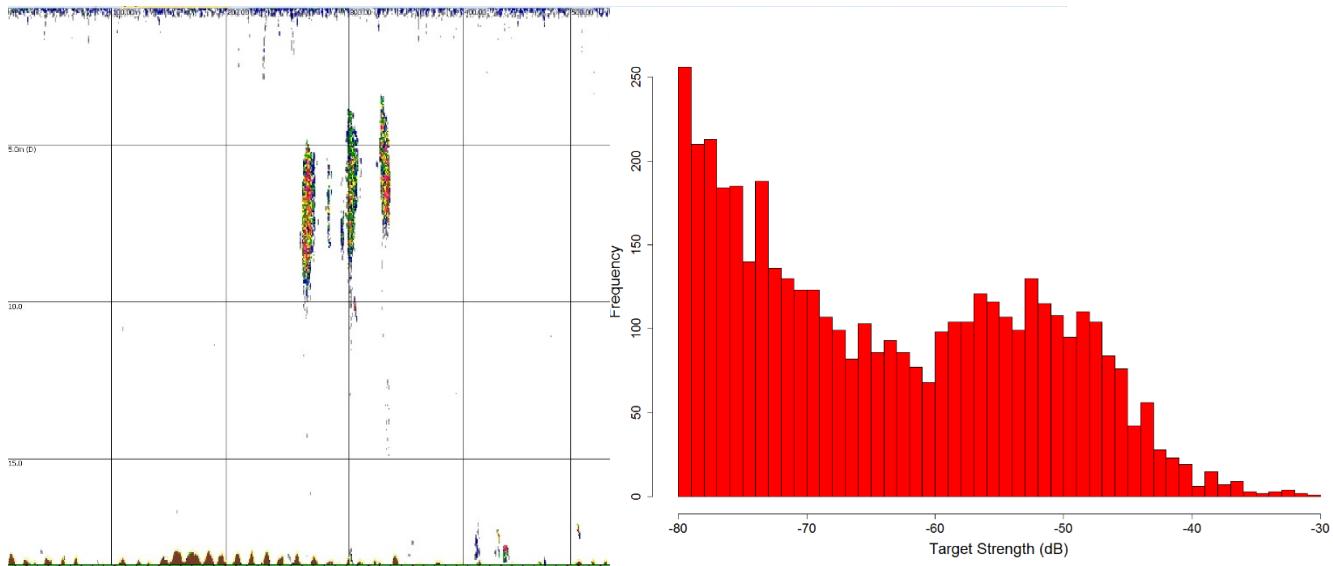


Figure 11. Echogram (left) and the resultant TS histogram (right) for each echo in the menhaden school. There are 7727 echoes that meet the single-target detection criteria initially.

For fish aggregations, echoes from individual fish will vary in their returned target strength due to differences in their morphology as well as their relative orientation to the acoustic wavefront. There are additional scatterering processes that may also occur coincident with a fish aggregation which tend to complicate the TS distribution due to background noise, bubbles, and zooplankton.. TS data are thresholded at -65 dB to remove these weak scatterers and still maintain the echoes from the fish targets (Figure 12). A maximum TS threshold was set to -20 dB which excludes contamination from bubbles or other surface processes.

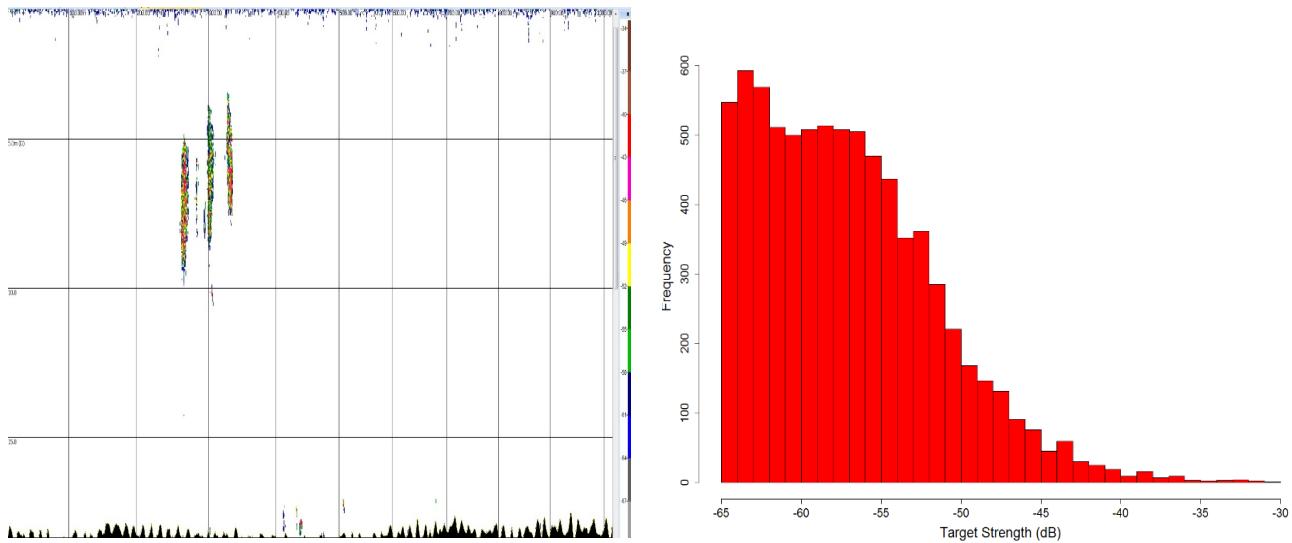


Figure 12. Echogram (left) and the resultant TS histogram (right) for each echo in the menhaden school after the thresholding processes. There are now 4480 echoes that meet the single-target detection criteria initially.

Once thresholded, a single target detection method for split-beam echosounders can be applied to filter out echoes that are likely to from overlapping multiple targets. For this algorithm, detection parameters were set with the following criteria: maximum beam compensation of 12 dB, maximum standard deviation of minor- and major-axis angles of 3.0, pulse length determination level of 6, 0.7 to 1.5 minimum to maximum normalized pulse length, and a Simrad LOBE beam compensation model. Before overlapping echoes are removed by this algorithm, the mean TS (calculated in the linear domain) was approximately -52.0 dB; after single target detection, the TS mean increased to -41.6 dB (Figure 13). This increase in TS due to removal of weaker targets from multiple scattering processes will produce a significant (order of magnitude) change in any estimates of biomass from the overall scattering aggregation.

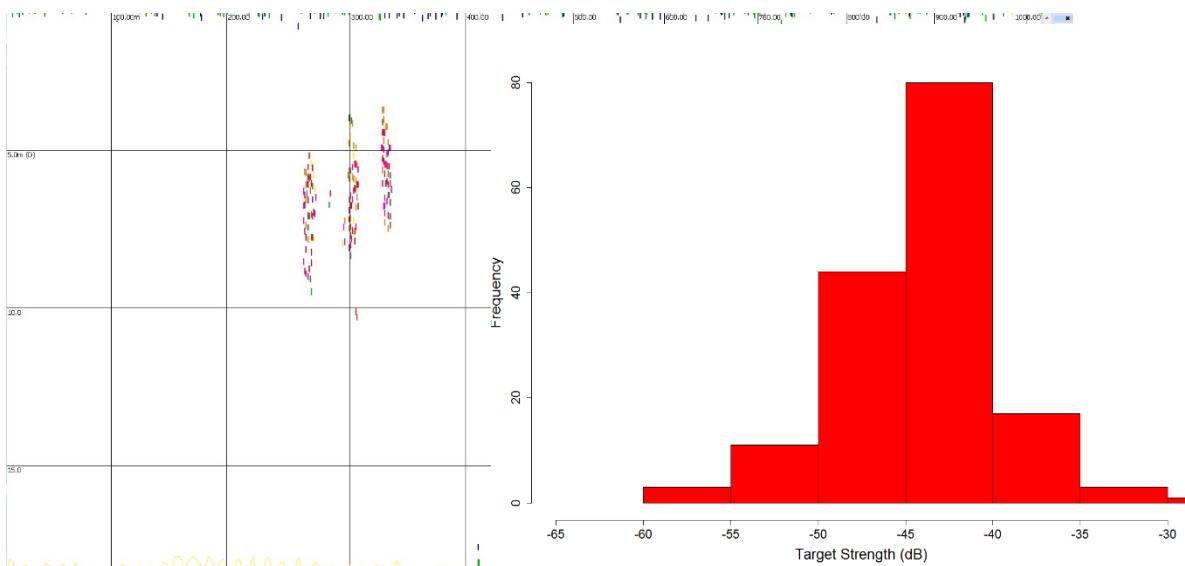


Figure 13. Echogram (left) and the resultant TS histogram (right) for each echo in the menhaden school after thresholding and single-target detection criteria are applied. There are now 159 echoes that meet the single-target criteria.

While this algorithm decreases the likelihood that an accepted echo comprises multiple echoes, additional diagnostic methods can be applied for additional validation. One such tool is the Sawada Index, a formula that estimates the number of targets per reverberation volume:

$$N_v = \frac{c\tau\psi r^2 Nei}{2}$$

Whereby N_v is the number of targets per reverberation volume, c is the speed of sound (m/s), ψ is the equivalent beam angle (the linear transform of 1 dB re 1 str), τ is the pulse width (ms), r is the range of the ensonified volume, and Nei is the acoustic approximation for fish density:

$$Nei = 10^{(S_v/10)} / 10^{(TS/10)}$$

Both TS and S_v values were smoothed over a 10 ping (horizontal) x 2m (vertical) resolution grid and were used to calculate the Sawada Index for multiple bins. Since the Sawada Index can be interpreted as the likelihood an echo is overlapping or not, echoes that had a N_v of greater than 0.20 were rejected.

When comparing the TS values from the single target detection and Sawada Index outputs, the mean TS decreased to -43.9 dB with 60 single targets being rejected under additional scrutiny (Figure 14).

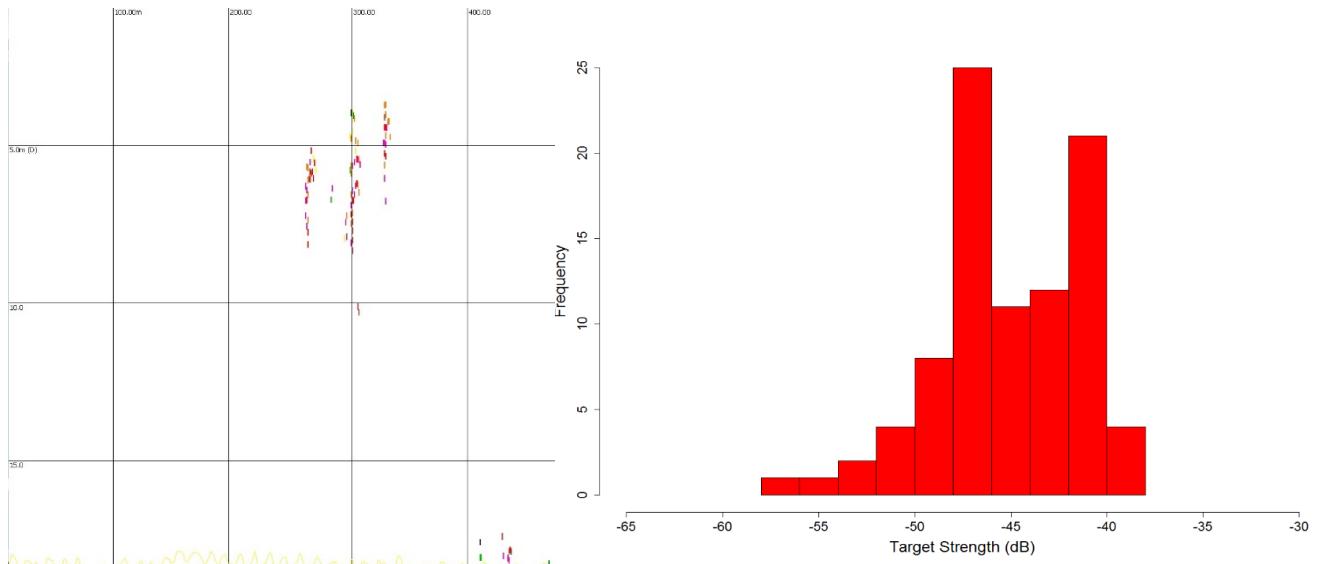


Figure 14. Echogram (left) and the resultant TS histogram (right) for each echo in the menhaden school after application of the Sawada criteria. There are now 89 echoes that meet the single-target detection criteria.

Retrieving an accurate TS value from a single target is imperative in order to generate abundance and biomass estimates with greater certainty and precision. If the mean S_v for this menhaden aggregation was approximately -39.8 after removing background noise and thresholding out weak and strong scatterers unlikely to be fish, that would result in fish densities of 16.630, 1.537, and 2.593 fish/m³ when using the processed, single target, and post-Sawada TS values. In order to verify and ground-truth the predicted fish densities that result from the different single-target detection criteria, we are analyzing video data (Figure 15) from fish aggregations to produce estimates of fish-packing density (and variability) as well as inter-fish spacing which we can use to construct theoretical scattering models to test our detection methods.



Figure 15. Underwater video footage of an Atlantic menhaden school collected in September 2015. Fish density (# / m³) can be estimated for various schools as well as how the fish density changes for a given school both spatially (i.e. different parts of the school), temporally (during the observation period), and as a function of fish behavior (i.e. turning, compressing/expanding). Initial observations of the video data suggest that the school dynamics create a large amount of variability as to whether multiple scattering processes are likely to occur.

IMPACT/APPLICATION

The use of acoustics in coastal waters for sensing and detection requires understanding the natural sources of variance in propagation, attenuation, and scattering. Recent work has revealed that aggregations of fish and other biota are, in some cases, the largest sources of this variance. We will extend these studies to make quantitative predictions about scattering, propagation, and attenuation at low to mid frequencies from aggregations of two abundant, large species off the west coast of North America, an important navy tactical and training area. These species have remarkably different morphologies and internal characteristics, yet both show strong scattering over the same range of frequencies, presenting a unique opportunity to evaluate the mechanisms of scattering from individual animals as well as mono- and hetero-specific aggregations. The models, measurements, and predictions resulting from this work will be directly applicable to naval operations within the habitat of hake and squid and will extend our general understanding of biologically driven acoustic processes.

RELATED PROJECTS

This work is part of a Basic Research Challenge initiative of Fish Acoustics and is related to the other projects within this initiative. Most notably, some field work for this project was conducted in conjunction with efforts by Gauss et al. and Diachok.

PUBLICATIONS (* student co-author)

K.N. Becker* and **J.D. Warren** (2015) ``Material properties of Pacific hake, Humboldt squid, and two species of myctophids in the California Current.'' Journal of the Acoustical Society of America. 137(5): 2522-2532. doi: 10.1121/1.4919308

K.N. Becker* and **J.D. Warren** (2014) ``Material properties of Northeast Pacific zooplankton." ICES Journal of Marine Science. 71(9): 2550-2563. doi: 10.1093/icesjms/fsu109

PRESENTATIONS (* student co-author)

J.D. Warren and *K.N. Becker**. A tale of two coasts: Material properties of North Pacific nekton and zooplankton and coastal Atlantic forage fish. ICES Working Group on Fisheries Acoustics, Science, and Technology. New Bedford, Massachusetts. May 2014.

*S.S. Urmey** and J.D. Warren. Model-based and in-situ observations of high-frequency (10s–100s kHz) acoustic scattering from multiple targets. 167th Meeting of the Acoustical Society of America. Providence, Rhode Island. May 2014.

*K.N. Becker** and J.D. Warren. Material properties of Pacific hake, Humboldt squid, and two species of myctophids in the California Current. 167th Meeting of the Acoustical Society of America. Providence, Rhode Island. May 2014.

J.D. Warren, *K.N. Becker**, D. Chu, K. Benoit-Bird. Acoustic scattering characteristics of pelagic and coastal nekton. 167th Meeting of the Acoustical Society of America. Providence, Rhode Island. May 2014.

2011 Promotion to Associate Professor (with tenure)